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Executive summary

This is Deliverable 6.1 **Report on the connections between "Extreme Marine Events" and Biological EOVs**. Evolving *Extreme Marine Events* linked to climate change can cause adverse effects on the marine environment. Such *Extreme Marine Events* are of major concern from both the economical (e.g., fisheries and aquaculture) and ecological (environmental preservation) points of view. The objective of this report is to provide a description and examples of the links between the occurrence of a selection of *Extreme Marine Events* (marine heatwaves, deoxygenation and acidification) and the impacts they have on the marine biota. A literature review and some case studies from EuroSea target regions are presented, in which physical or chemical data describing *Extreme Marine Events* are overlaid with biological data.

Introduction

The ocean plays an active role as both a driver and a recipient of climate change. Thus, by storing heat and capturing atmospheric CO_2, the ocean contributes to mitigating the greenhouse effect. This significant intervention in the climate system has environmental costs for the ocean domain itself, as it leads to a gradual warming of the water column, a decrease in seawater pH, known as ocean acidification, and a decrease in dissolved oxygen levels, known as deoxygenation. These three anthropogenic disturbances pose the most serious current biogeochemical threat to marine ecosystems, the consequences of which have already been documented through changes in the circulation of water masses, progressive acidification rates and increasing deoxygenated zones. For this reason, temperature, pH and oxygen have been included by UNESCO as indicators to be monitored under Goal 14 of the Sustainable Development Goals (SDGs). However, the chemistry and physics of water bodies also respond to natural processes, and it is therefore essential to distinguish the fraction of variability due to human action from that of natural origin. This analysis of variability allows the estimation of the time of emergence (ToE), i.e. the time horizon over which projected environmental conditions differ distinctly from past conditions due to climate change.

Climate change is the greatest challenge facing humanity in the 21st century. The global warming reported in the Fifth Assessment Report (AR5) on the state of our planet's climate by the Intergovernmental Panel on Climate Change (IPCC) has already had visible consequences, particularly in the increase in the Earth's mean surface temperature and ocean heat content (Stocker, 2014; Pachauri *et al.*, 2014). The findings in AR5 have been confirmed in the recent IPCC Special Report on Oceans and Cryosphere in a Changing Climate, published in September 2019. On average, over the past 50 years, about 93 % of the excess heat accumulated in the climate system from the greenhouse effect associated with anthropogenic gas emissions, especially carbon dioxide (CO_2), has been stored in the ocean (IPCC, 2022). Warming of the upper ocean layer (0-700 meters) has led to increased stratification of the water column and changes in ocean circulation mechanisms (Caesar *et al.,* 2018; IPCC, 2022). However, heat storage also leads to a decrease in dissolved oxygen levels (oceanic deoxygenation), both through the direct effect of temperature on gas solubility and the indirect effect of increased stratification on the reduction of oxygen supply to the deeper layers (Keeling et al., 2010). In the period between 1970 and 2010, the ocean lost between 0.3 and 3.8 % of the oxygen inventory in the top 1,000 metres (Schmidtko *et al.*, 2017, IPCC, 2022) and it is anticipated that more deoxygenated marine areas will appear in the future in response to global change (Frölicher and Laufkötter, 2018; IPCC, 2022).

To sum up, ocean climate change can cause different adverse effects, including:

a. **Ocean warming**. The generalised increase in seawater temperature due to atmospheric warming and air-sea heat exchange. As a result, the frequency, duration and intensity of Marine Heat Waves (MHW) are expected to increase in many regions globally.

b. **Ocean deoxygenation.** Ocean warming reduces oxygen solubility, and enhanced stratification reduces the ventilation of the ocean interior, resulting in the expansion of the so-called "Oxygen Minimum Zones" (OMZ).

c. **Ocean acidification.** As larger amounts of CO_2 emissions are released into the atmosphere, the ocean intake of CO_2 increases too, decreasing seawater pH and affecting the formation of hard skeletons in some marine species.

In this document, the effect of these processes on marine biota are discussed through a literature review presenting the current knowledge on this subject, and through different case studies concerning species that are relevant from the ecological or economical point of view.

Section 1 presents the literature review of each of the processes (marine heat waves, ocean deoxygenation and ocean acidification) and the methods used to investigate these processes. Section 2 presents the biological datasets used in the case studies. Section 3 describes the case studies considered here, with examples on the interaction between extreme marine events and relevant biota.

1. Extreme Marine Events

1.1. Marine Heat Waves

Overview

Climate change in the marine environment can have unintended adverse effects, one of the most well-known being a long-term, steady increase in seawater temperature in many regions of the world ocean. In addition to this long-term, climatological effect, the frequency and intensity of short-lived, extreme meteorological events are also expected to increase. Such sharp events create stressful conditions for the marine biota and can trigger widespread mortality of important habitat-forming species.

Marine Heat Waves (MHWs), characterised by high seawater temperature anomalies, are an example of such extreme marine events that can have a strong impact on the structure and functioning of marine communities (Hobday *et al.*, 2016). There are multiple examples in the literature from recent decades on the impact of MHWs on ocean ecosystem health. For example, after the strong 2010-2011 La Niña event, an abnormal intensification of the warm poleward Leeuwin current, which transports water along western Australia, caused an unprecedented increase in sea surface temperature, with 5°C deviations above the climatological values over a fortnight (Feng *et al*., 2013). This event caused major shifts in the biodiversity patterns of many fish species, sessile invertebrates and was responsible for reducing the abundance of habitat-forming temperate seaweeds (Wernberg *et al.*, 2013).

In the Mediterranean Sea, sea surface temperature anomalies of 2-3°C above normal levels were recorded during the summer heatwave of 2003. Enhanced air-sea heat exchange together with reduced mixing under weak wind conditions led to a situation of increased thermal stratification that triggered widespread mortality of benthic invertebrates (Garrabou *et al*., 2009) and reduced seagrass meadows coverage (Marbà and Duarte, 2010).

More recently, the trends in the number, duration and intensity of MHWs across the Mediterranean Sea were examined in detail at the regional level (Juza et al., 2022; EuroSea project WP6 activities related to this report). One important conclusion of this work is that **all the MHW indicators (frequency, duration, intensity) in the surface Mediterranean Sea have increased in magnitude during the last four decades**. Varying trends were observed across the different sub-regions in the Mediterranean Sea ranging from 0.06 °C to 0.13 °C per decade for the MHW mean intensity, 0.26 °C to 0.55 °C per decade for MHW maximum intensity, 1.23 days to 3.82 days per decade for the MHW duration and 1.1 to 1.8 events per decade for the MHW frequency. Increased occurrence and intensity of MHWs leads to enhanced thermal stratification, in particular in summer and autumn, whereas higher MHW indices extend towards the interior due to wind-driven mixing and weakened stratification (Juza *et al.*, 2022).

In this Section, research on MHW occurrence and intensity in waters off SW Ireland is presented. Here, the Hobday *et al*. (2016) definition of a MHW is used: an anomalously warm event is characterised by at least 5 days of seawater temperatures above the 90th percentile of a temperature climatology. Southwest Ireland was selected as the marine study area due to its importance for both ecology and the aquaculture, with numerous Special Areas of Conservation in the region and widespread aquaculture farming activity.

Methods

The occurrence of MHWs in SW Irish waters was examined using an application of the Regional Ocean Modelling System, ROMS, a three-dimensional, hydrostatic, primitive-equation and terrain-following numerical ocean model (Shchepetkin and McWilliams, 2005). The application for SW Ireland (Fig. 1) provides a horizontal resolution of 1 km with 30 vertical sigma layers. Bathymetry was derived from the INFOMAR[1] (Integrated Mapping for the Sustainable Development of Ireland's Marine Resource) and GEBCO[2] (General Bathymetric Chart of the Oceans) databases. The TPXO8[3] (TOPEX/Poseidon global ocean tide model ver. 8.0) global inverse barotropic tide model (Egbert and Erofeeva, 2002) was applied to enter the tidal elevations and barotropic velocities at the boundaries. Open boundary conditions were prescribed from the Iberian-Biscay-Irish Reanalysis Model (Sotillo *et al.,* 2015); the NEMO v3.6 application is available from CMEMS[4] (Copernicus Marine Environmental Monitoring Services ID: IBI_REANALYSIS_PHYS_005_002). Surface forcing was derived from MÉRA[5] (Met Éireann Reanalysis), an atmospheric reanalysis product generated by the Met Éireann, the Irish national meteorological agency. For a detailed description of the hydrodynamic model, the reader is referred to Nagy *et al.* (2021). Daily fields of seawater temperature were determined from this model from 1993 to 2016.

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[1] http://www.infomar.ie/

[2] https://www.gebco.net/

[3] https://www.tpxo.net/global/tpxo8-atlas

[4] https://marine.copernicus.eu/

[5] https://www.met.ie/climate/available-data/mera#:~:text=Met%20%C3%89ireann%20Re%2DAnalysis%20%E2%80%93%20Climate%20Re%2Danalysis&text=Climate%20reanalysis%20is%20a%20systematic,for%20climate%20monitoring%20and%20research.

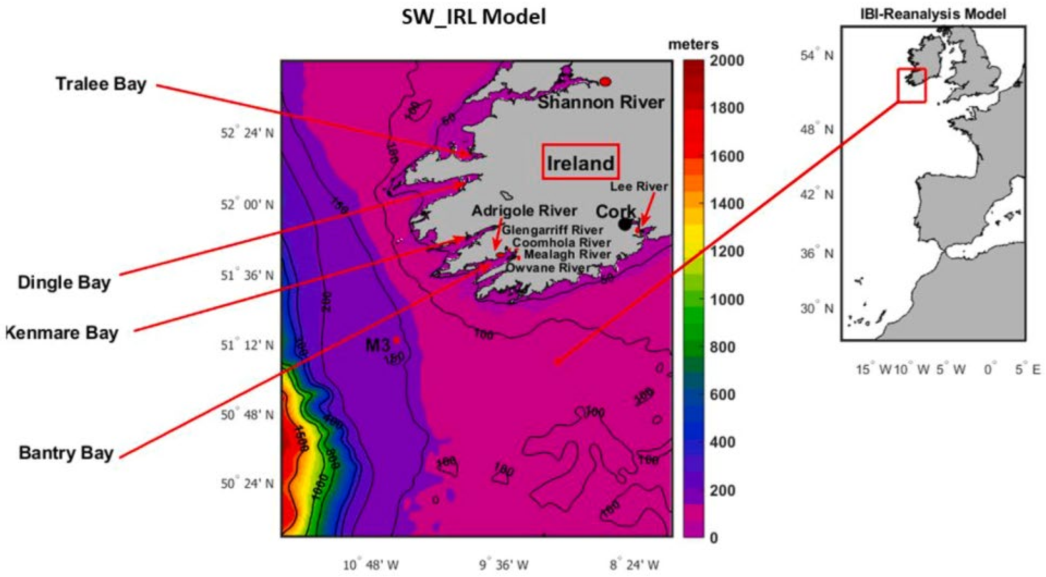

Figure 1. The Southwest of Ireland model domain (left) nested in the Iberian-Biscay-Irish domain (right). Source: Nagy et al. (2021).

The definition, analysis and recommendations described in Hobday *et al.* (2016) were applied to the surface and seabed daily seawater temperature fields to identify the occurrence, duration and intensity of MHWs in the region. First, the climatology and 90th percentile threshold was determined from the local seawater temperature distribution for the reference period 1993-2014 (22 years in length), for consistency with the Copernicus Marine Service Ocean State Report 2018 for evaluation of anomalies. Then, the climatology and 90th percentile threshold was smoothed using a 30-day moving average window. Marine Heat Waves were considered as any event when the temperature signal exceeds the 90th threshold for at least 5 days. In addition, two consecutive events separated by 2 days or less were considered the same MHW. The analysis covered the period 1993-2016.

Results

Figure 2 below shows results of the MHW analysis using the surface layer of the local high-resolution Southwest Ireland model. The spatial pattern results of average frequency (Fig. 2a), duration (Fig. 2b) and intensity (Fig. 2c) of MHWs in this NE Atlantic local model do not exhibit the same magnitude of change as that observed in the Mediterranean (Juza *et al.*, 2022). This is likely related to the complex oceanography off SW Ireland (e.g. Holliday *et al.* 2020, Hill *et al.* 2012). The average MHW intensity (Fig. 2.c) is higher in near-coastal waters. This is a relevant result for both: (a) the aquaculture activities located in this area, and (b) the biological communities that are examined to determine ocean health status for the purposes of WFD monitoring. While the average number of MHWs in the study area was only between 1 to 3 per year (Fig. 2a), certain regions showed a positive linear trend (significant at the 95 % confidence level; black dots in Fig 2e) for MHW duration (Fig. 2e) and MHW intensity (Fig. 2f). In particular, the areas where there is a significant, positive trend in MHW duration (Fig. 2e) match the offshore areas along which the Irish coastal current flows, transporting phytoplankton and larvae around the coast. Therefore, this may be an important result from a future monitoring, risk and assessment point of view, and supports the idea that frequent monitoring in offshore waters is as necessary as in the very near-coastal waters, the latter being already frequently monitored as part of the national phytoplankton, Harmful Algal Bloom and biotoxin monitoring programmes and other Directive related environmental assessments e.g. Water Framework Directive. Efforts need to be extended further offshore, to cover the areas with positive trends in MHW duration are observed (Fig. 2e).

This validated numerical ocean model (using *in-situ* ocean observations) simulated **MHWs that became longer and more intense in the period 1993-2016**, which could reflect the effects of climate change and ocean warming in this part of the ocean.

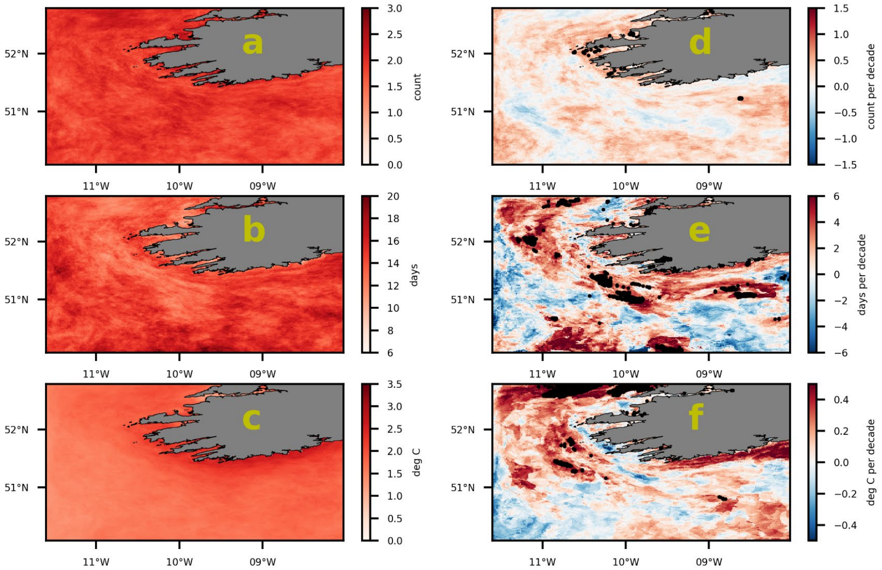

Figure 2. Surface water Marine Heat Wave statistics for SW Irish waters between 1993 and 2016. Where 2a (average), 2d (trend) = MHW frequency (number of events per year); 2b (average), 2e (trend) = MHW duration in days; 2c (average), 2f (trend) = maximum intensity. Black dots indicate regions where the trend is significant at the 95 % confidence level.

1.2. Ocean deoxygenation

Overview

The total oxygen content of the ocean has been decreasing since the mid-twentieth century, and this has resulted in an expansion of the so-called "Ocean Minimum Zones" (Stramma *et al.*, 2008). The drop in the dissolved oxygen concentration is a consequence of global warming. Predicted declines by the year 2100 vary from 2 to 12 µmol kg^{-1} depending on the model (Keeling *et al.*, 2010). This will likely have serious consequences for marine life with significant size reductions from microbes (> 20 %) to macrofauna expected (Deutch *et al.,* 2022).

The main driver behind the expansion of the Ocean Minimum Zones is the reduced ventilation of the ocean interior (Helm *et al.*, 2011). Climate change is increasing worldwide atmospheric temperatures and, as a result, the air-sea heat exchange is enhanced, causing sea surface temperatures to rise. In addition, a warmer climate leads to increased melting of glaciers and sea ice in high latitudes, thus resulting in greater amounts of freshwater released into the ocean. Warmer and fresher waters at the surface means that climate change will enhance stratification in some parts of the ocean. Therefore, mixing is diminished, as it is the formation of deep-water masses, which carry oxygen-rich waters towards the deep ocean. The immediate consequence is a reduced ventilation and dropping of the dissolved oxygen concentration in the ocean interior, with devastating effects for marine life (Sarmiento *et al.,* 1998, Matear *et al.,* 2000, Plattner *et al.*, 2001, Bopp *et al.*, 2002, Keeling and Garcia, 2002).

Dynamics of O_2 in the ocean and how deoxygenation occurs. The content of oxygen in seawater is the result of the interaction of physical, biogeochemical and biological processes. In an under-saturated surface water body, oxygen flows from the atmosphere to the ocean at the air-sea interface. The solubility of oxygen strongly depends on seawater temperature, with ocean warming decreasing the solubility of this gas. In fact, it is estimated that, in the context of climate change, around 15 % of the total ocean deoxygenation is because of a reduced oxygen solubility, whereas the remaining 85 % decrease in global dissolved oxygen content would be due to decreased ventilation, which results from a higher water column stratification and lower air-sea mixing (Helm *et al.*, 2011).

At the surface and well-lit layer of the ocean, photosynthesis releases oxygen as a by-product. However, deeper in the ocean, photosynthesis is not possible and the amount of dissolved oxygen of a deep-water body over time will depend on: (a) the initial dissolved oxygen concentration, (b) the Oxygen Utilization Rate, and (c) the ventilation age (Keeling *et al.*, 2010). The starting oxygen content largely depends on the seawater temperature and mixing conditions when the water body was at the surface and in contact with the atmosphere. The Oxygen Utilisation Rate is determined by the amount of organic matter present and the seawater temperature. Beneath high productivity areas, Particulate Organic Matter (POM) starts sinking towards the seafloor, and the remineralisation of the organic matter consumes oxygen. This remineralisation process explains the location of Oxygen Minimum Zones, which typically extend over depths between 400 m - 1200 m.

In addition, higher respiration rates occur under warmer conditions (Altieri *et al.*, 2015; Brown *et al.*, 2004). This shows how multiple stressors are connected to each other, with ocean warming exacerbating the problem of ocean deoxygenation. Furthermore, enhanced respiration rates release larger volumes of CO_2, a by-product of aerobic respiration, thus aggravating the issue of ocean acidification (Gobler and Baumann, 2016).

A dissolved oxygen (DO) threshold of 60 µg kg^{-1} is typically used to define hypoxic conditions when the dissolved oxygen concentration falls below that level (Gray *et al.*, 2002). Under hypoxic conditions, aerobic life becomes increasingly difficult, and other forms of metabolism benefit. Denitrification (using nitrate or NO_3 as the main electron acceptor) and anammox (the anaerobic oxidation of ammonia) replace aerobic respiration and remove biologically available forms of nitrogen by releasing nitrogen gas (N_2), which is biologically unavailable for most organisms. This reduces the supply of nitrate, a limiting nutrient for ocean productivity (Codispoti *et al.*, 2001; Gruber, 2004). Moreover, nitrous oxide (N_2O), a known powerful greenhouse gas often associated with agricultural activities, is released as well (Codispoti *et al.* 2001; Jin and Gruber 2003; Nevison *et al.* 2003). As a result, global warming would become a self-sustaining process (Gruber 2008), with increased seawater temperatures accelerating respiration rates and oxygen consumption, and the subsequent anaerobic, nitrogen-based respiration releasing N_2O into the ocean and atmosphere through air-sea gas exchange. Methane (CH_4), a frequent by-product of biological respiration in anaerobic communities and an important greenhouse gas is unlikely to reach the atmosphere due to the activity of methanotrophic bacteria (Naqvi *et al.*, 2010). Under anoxic conditions, toxic sulphide (S^{2-}) is released.

In coastal waters, deoxygenation can take place when large amounts of inorganic nutrients are released into the marine environment through water pollution from agricultural activities, untreated human sewage or freshwater discharge among other (Fig. 3). This triggers a vigorous growth of microalgae and enhanced primary production. The subsequent decomposition of organic matter, in conjunction with low ventilation conditions in an enclosed coastal basin, can result in a dramatic drop in dissolved oxygen concentration (Diaz and Rosenberg 1995; Breitburg *et al.*, 2009) and mass mortality of marine life. An example of coastal eutrophication causing widespread mortality is the case of Mar Menor, in SE Spain (Álvarez-Rogel *et al.*, 2020). In addition, a large bloom of *Karenia mikimotoi* occurred in summer 2005 in Irish waters, when an extensive decimation of faunal communities was documented in several locations due to anoxic conditions (Silke *et al.*, 2005). Also, under adequate meteorological forcing, the upwelling of hypoxic waters from Oxygen Minimum Zones to the upper shelf can also cause sub-optimal oxygen concentrations in the coastal environment (Breitburg *et al.*, 2018; Chan *et al.*, 2008).

On the impact of deoxygenation on marine life. Deoxygenation affects biology at multiple levels of organisation, from environmentally-induced epigenetic modifications (Wang *et al.*, 2016) to individual and population distributions, through to trophic relationships and ecosystem structure (Breitburg *et al.*, 2018). Firstly, it is important to note that different species have widely varying oxygen tolerances, even in shallow coastal ecosystems. Therefore, it is difficult to generalise the effects that a particular deoxygenation event may have on the whole biological community, and instead known threshold tolerances can be useful for individual species (e.g., Kapetsky et al., 2013[6]).

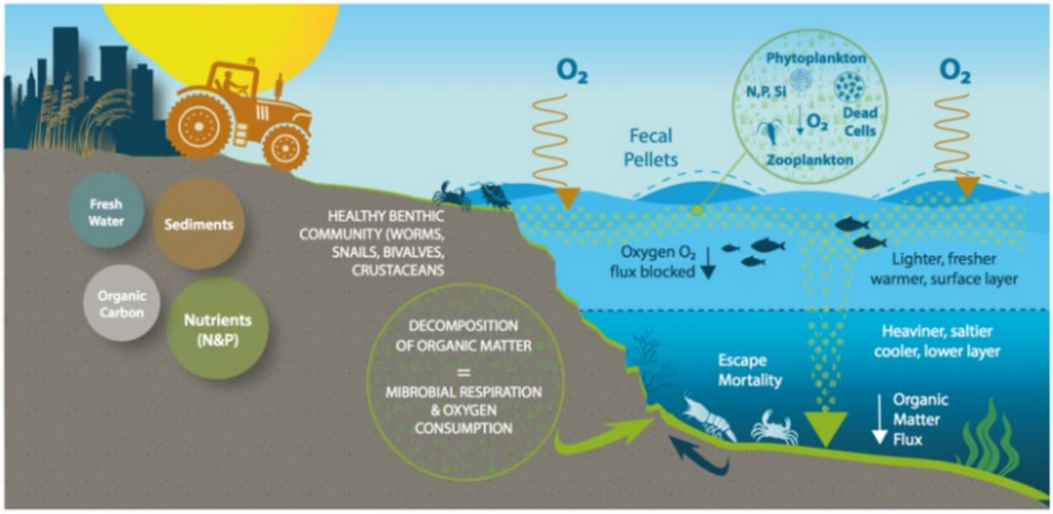

Figure 3. Impacts of eutrophication on ocean oxygen. Source: Global Ocean Oxygen Network, Breitburg, D., M., Gregoire, K. Isensee (eds.) 2018. The ocean is losing its breath: Declining oxygen in the world's ocean and coastal waters. IOC-UNESCO, IOC Technical Series, No. 137 40pp. (IOC/2018/TS/137)

On the individual level, low dissolved oxygen concentration levels reduce growth and survival, and trigger behavioural alterations. Reproduction is impaired when the oxygen availability is reduced as it impacts the energy allocation to gametogenesis. In general, hypoxic conditions interfere with the gametogenesis, the neuroendocrine function and hormone production. The impact in reproduction affects population growth and can reduce fisheries yield (Sokolova, 2013; Thomas *et al.*, 2015; Rose *et al.*, 2017). In summary, the repeated exposure to low dissolved oxygen concentrations can alter immune responses, increase risk of disease and reduce growth (Keppel *et al.*, 2015; Stierhoff *et al.*, 2009).

Among many other factors, organisms are distributed in the marine environment in correspondence with the availability of oxygen. Since migratory behaviours depend on the availability of oxygen, the distribution of prey and predators is conditioned by the existence of hypoxic zones (Breitburg *et al.*, 2002; Gilly *et al.*, 2013).

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[6] https://longline.co.uk/meta/list

As mentioned above, the tolerances to different ranges of dissolved oxygen concentration and the associated behavioural responses to hypoxic conditions widely vary among species, taxa and trophic groups (Vaquer-Sunyer and Duarte, 2008). As a result, the frequency of predator-prey encounters, feeding opportunities and the food web structure are affected. The extension of the Oxygen Minimum Zones reduces the extent of suitable habitat types and diel migration (Stramma *et al.*, 2012). Hypoxic-induced habitat compressions means that the organisms are confined to a smaller space either above (surface waters) or beneath (toward the seabed) the hypoxic zone. The consequences of this are limited room to hide from predators and the increased competition for resources, both for pelagic and demersal species (Eby and Crowder, 2002). On the other hand, habitat compression may be beneficial for some organisms particularly tolerant to the hypoxic conditions, which would find it easier to avoid predators and face less competition for catching hypoxic-tolerant prey (Seibel, 2011; Ekau *et al.*, 2010). In other words, hypoxic tolerant fish and invertebrates can benefit from the expansion of Oxygen Minimum Zones as predators and competitors are excluded (Gallo and Levin, 2016; Sato *et al.*, 2017).

The need for a Global Ocean O_2 Database (GO_2DAT). Even though there is evidence that ocean deoxygenation poses a serious threat to ocean health, there are still large uncertainties on the extent of the problem that could be attributable to the scarcity of accessible data. The lack of observations do not allow a quantitative assessment of the severity of deoxygenation in the global ocean. This is particularly important in regions where specific institutions and infrastructure for data collection do not exist. Furthermore, short-term or short-scale variability and high non-linearity in coastal waters require a higher data acquisition resolution. For a proper understanding and assessment of the deoxygenation in a warming ocean, there is a need for coherent and comprehensive observational O_2 datasets. GO_2DAT is an initiative that aims to create such a consistent and international dataset, integrating O_2 observations from multiple platforms around the world, different measuring techniques and following the FAIR principles: Findable, Accessible, Interoperable, and Reusable (Grégoire *et al.*, 2021).

Methods

In-situ measurements of the dissolved oxygen concentration in seawater are derived from three major methods: (a) Winkler titration, (b) electrochemical approaches and (c) optical sensors. *In-situ* observations (e.g. on-board analysis through initiatives such as GO-SHIP[7] to collect high quality data) offer the most reliable and accurate data of the oxygen content in the ocean. Unfortunately, *in-situ* measurements are scarce, and for long-term studies of the effects of climate change on the biota, long time series are necessary, which are even scarcer.

Here, in order to overcome the lack of *in-situ* data, biogeochemical models were used. Marine biogeochemical models can quantify several aspects of the ocean biogeochemistry, including the cycling of nutrients, plankton distribution and primary productivity. Oxygen time series presented here were derived from the CMEMS' Atlantic Iberian-Biscay-Irish Biogeochemistry Multi-Year Non-Assimilative Hindcast Product, based on the PISCES biogeochemical model and providing 3D fields at 1/12° resolution starting from 1993 for the area 26ºN, 19ºW to 56ºN, 05ºE.

Unlike Marine Heat Waves, a formal, consistent and widely accepted definition of what an O_2 Extreme Marine Event is could not be found in the scientific literature, since most studies focus on the long-term effects of climate change, and not on sudden localized extreme events. For this reason, a similar methodology to the

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[7] https://www.go-ship.org/

one used for Marine Heat Waves is presented and applied to Case Study 5.1. The idea is to define a minimum oxygen event as any period when the dissolved oxygen concentration falls below the 10th percentile threshold for at least 5 days. The climatology and 10th percentile threshold is defined over the basis of the longest available time series.

1.3. Ocean acidification

Overview

The atmospheric concentration of carbon dioxide (CO_2) has increased significantly since the beginning of the industrial era. Among the causes are the release of carbon from fossil fuel combustion, deforestation and land-use changes. Anthropogenic emissions have become the dominant source of CO_2 to the atmosphere and continue increasing (Le Quéré *et al.*, 2018). The global ocean plays a significant role in mitigating this increase through the absorption of approximately one quarter of the emissions (Le Quéré *et al.*, 2018). Recently, the oceanic sink for anthropogenic CO_2 (C_{ant}) has been estimated to represent 31% of the global emissions over the period 1994–2007 (Gruber *et al.*, 2019). Therefore, the withdrawal of atmospheric CO_2 by the ocean alleviates the greenhouse effect, albeit with the following downside: the CO_2 absorbed by the ocean changes seawater chemistry by lowering its pH and the carbonate ion (CO_2^{3-}) levels. These chemical reactions are generally referred to as ocean acidification (Doney *et al.*, 2009) and threaten the overall structure of marine ecosystems on a global scale (IGBP *et al.*, 2013). Ocean acidification trends have been previously documented through multidecadal measurements in open ocean marine observatories (Bates *et al.*, 2014). It is suggested that certain basins, such as the marginal seas, are more strongly impacted by the phenomenon than others (Lee *et al.*, 2011). Recent studies demonstrate that ocean acidification under elevated CO_2 and temperature levels could increase primary productivity of specific species (Holding *et al.*, 2015; Coello-Camba *et al.*, 2014; Li *et al.*, 2012). Moreover, such specific species-based primary productivity is also found to increase either by an increasing seawater CO_2 levels (Kim *et al.*, 2006; Olischläger *et al.*, 2013) or elevated temperature alone due to the effects of global warming (Yvon-Durocher *et al.*, 2015; Lewandowska *et al.*, 2012).

Ocean acidification is responsible for changes in the oceanic carbonate system, resulting in impacts on partial pressure of CO_2 (pCO_2), DIC, pH, alkalinity, and calcium carbonate saturation state (Feely et al., 2010; Beaufort *et al.*, 2011). In the case of calcifying organisms, there is a clear trend of decreasing calcification with increasing pCO_2, which follows the corresponding decreasing concentrations of CO_2^{3-} as a consequence of decreasing pH (Beaufort *et al.*, 2011). These effects cause a decline in shellfish calcification and growth rates (Talmage and Gobler, 2010; Wittmann and Pörtner, 2013), as well as of shell-forming marine plankton and benthic organisms including corals (Kleypas *et al.*, 1999; Doney *et al.*, 2009; Beaufort *et al.*, 2011). The latter have already disappeared or are significantly damaged in some coastal areas around the world, including Indonesia, Hawaii, the Caribbean, Fiji, Maldives, and Australia (Erez *et al.*, 2011). A 30 % decline or damage of coral reef ecosystems is estimated worldwide, with predictions that as high as 60 % of the global coral reefs may disappear by 2030 (Hughes *et al.*, 2003). In the case of the Mediterranean Sea (MedSea), with high sensitivity to acidification attributed to particular biogeochemical features and water circulation patterns. The high alkalinity of Mediterranean waters and an active overturning circulation result in an increased absorption of atmospheric CO_2 and intensified carbon transport from the surface to the ocean interior (Lee *et al.*, 2011; Hassoun *et al.*, 2015). Moreover, C_{ant} is continuously imported from the North Atlantic through the Strait of Gibraltar (Palmieri *et al.*, 2015; Huertas *et al.*, 2009), Spain, resulting in a long-term accumulation in the basin. The Mediterranean Sea is experiencing a decrease in pH (Palmieri *et al.*, 2015; Huertas *et al.*, 2009). Another example, in the North Atlantic, describes an increase of anthropogenic carbon in near surface and deep waters (up to 2500 m; Tanhua *et al.*, 2007). Off the Irish coast in NE Atlantic waters (Rockall Trough), in an area close to where susceptible deep cold water corals reside, ocean observation measurements show that near surface pH has declined by 0.03 pH units per decade and a shoaling of the aragonite saturation horizon (McGrath *et al.* 2012). Where aragonite is a form of calcium carbonate needed by calcifying organisms to produce skeletons/shells (e.g., corals and shellfish).

Ocean acidification includes several potential phenomena: 1) increasing dissolution of atmospheric CO_2 to seawater: anthropogenic ocean acidification; 2) input of CO_2 plus DIC upon mineralization of primary production influenced by elevated atmospheric CO_2: natural ocean acidification; 3) enhanced primary production and respiration due to the effects of global warming and other processes: natural ocean acidification; 4) direct acidification and stimulation of primary production by atmospheric acid rain: natural and anthropogenic ocean acidification. In addition, in coastal areas, the local geology and freshwater runoff can influence the seawater pH. A pictorial scheme of the main operational processes affecting the ocean acidification is depicted in Figure 4.

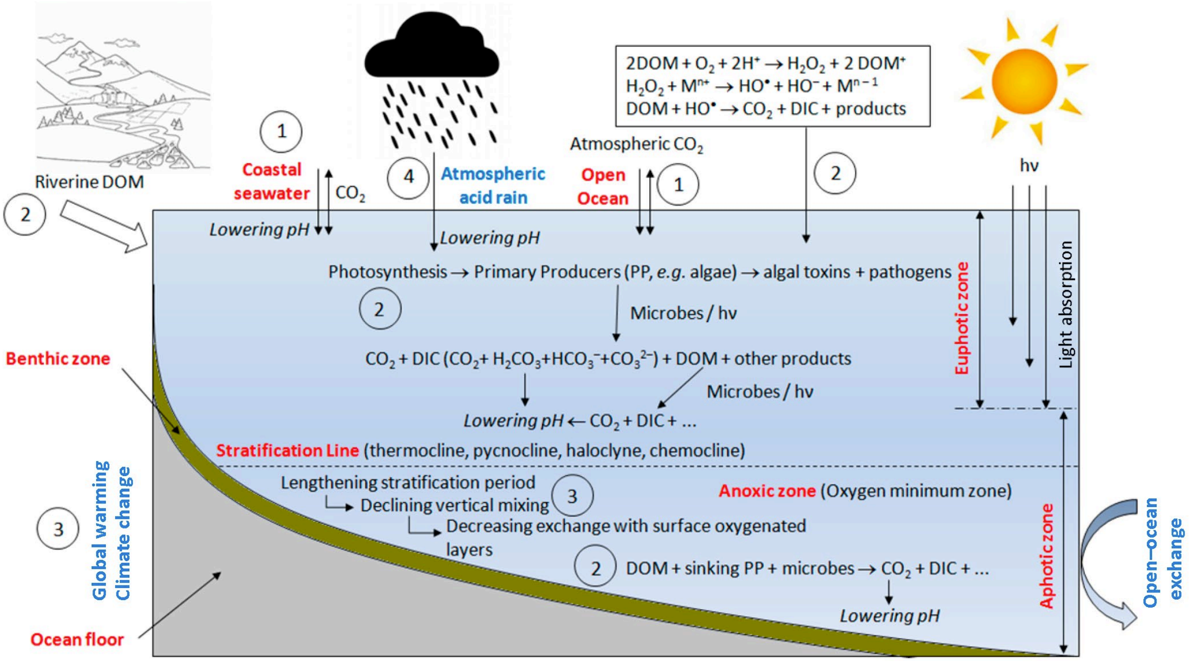

Figure 4. A conceptual model of acidification in coastal to open oceans, showing either dissolution of atmospheric carbon dioxide (CO_2) or emission of aquatic CO_2 plus dissolved inorganic carbon (DIC) originated from the photo induced and/or biological respiration of primary producers (PP). The latter includes both dissolved organic matter (DOM) and PP (1). Uptake of such CO_2 is primarily responsible for the occurrence of photosynthesis and PP (2) that can generate algal toxins or pathogens in the euphotic zone, along with generation of CO_2, DIC, and other products; PP can also be enhanced by autochthonous DOM (2), by DOM or sinking cells in subsurface or deeper seawater (2), and by riverine DOM (2). Atmospheric acid rain, mostly nitric acid or (HNO_3) and sulphuric acid (H_2SO_4) can contribute directly to the acidification (3). Global warming can lengthen the stratification period with a subsequent decline in vertical mixing, which reduces the exchange with surface oxygenated water (4) (from Mostafa et al., 2016).

This assessment requires the use of massive, long-term databases that allow, on the one hand, the estimation of temporal trends and, on the other, the differentiation between the aforementioned natural and anthropogenic components. Since 2005, researchers who are involved in the EuroSea project have been maintaining the Gibraltar Fixed time series (GIFT[8]; an oceanographic time series in the Strait of Gibraltar) that

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[8] https://twitter.com/water_ios_csic

contributes data to international climate change databases such as the Global Ocean Acidification Observing Network (GOA-ON[9]), the Carbon Dioxide Information Analysis Centre (CDIAC[10]) of the USA Department of Energy (DOE) and the International Oceanographic Data and Information Exchange Programme (IODE[11]) of UNESCO's Intergovernmental Oceanographic Commission (IOC) for the assessment of SDG indicator 14.3.

Methods

Similar to dissolved oxygen concentration, a lack of pH measurements and observed time series represents an important issue to study the long-term effects of climate change on the ocean pH. To overcome the lack of *in-situ* data, a biogeochemical model was used for investigative purposes[12].

Since the ocean is a buffered solution, extreme changes in short time scales of the ocean pH are not expected. For this reason, the focus here is on the long-term trends of ocean pH resulting from ocean acidification.

2. Marine biological datasets

2.1. EMODnet Seabed Habitats

In a world of climate change and increasing human uses of marine resources and coastal development, monitoring the status and trends of key indicators for healthy marine ecosystems is of paramount importance to inform environmental assessments. Essential Ocean Variables (EOVs) and Essential Biodiversity Variables (EBVs) constitute separate efforts to identify specific priority variables for monitoring (Muller-Karger *et al.*, 2018). The EOVs, described in Miloslavich *et al.* (2018), should provide baselines against which the impacts of climate change and anthropogenic pressures are measured and reported. EOVs describe the status of ecosystem components (e.g. plankton biomass and diversity, or abundance and distribution of fish, turtles, birds and mammals) and the extent and health of habitat-forming species, such as seagrass, macroalgae, mangrove and coral (Miloslavich *et al.*, 2018).

The maps in Figure 5 below show the distribution of three EOVs in European waters, published by the EMODnet Seabed Habitats group in 2019.

These EOVs are:

1. Seagrass cover. Seagrasses are the only flowering plants that grow in the marine environment. Seagrasses are found in both coastal and estuarine waters, forming dense, submerged meadows. Seagrasses play an important role in the ecosystem by providing nursery areas to different species of finfish, shellfish, turtles and marine mammals. In addition, seagrasses trap the underlying sediments and absorb nutrient runoff, thus contributing to a good water quality. Carbon sequestration in rhizomes and associated sediments makes up over 10 % of the total annual carbon burial in the sea. However, the extent of seagrass cover is declining worldwide due to coastal development and climate change.

Two species of seagrasses are found in the intertidal areas of Ireland: *Zostera marina* and *Zostera noltei*. Results from the Water Framework Directive monitoring programme of intertidal seagrasses in Ireland

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[9] http://www.goa-on.org/

[10] https://cdiac.ess-dive.lbl.gov/

[11] https://www.iode.org/

[12] https://doi.org/10.48670/moi-00028

revealed that most areas have a good or high ecological water quality status. Competition with opportunistic foliose green macroalgae (eutrophication indicator) was the reason behind a decline in seagrass extent in the few areas where a lower WFD status was found (Wilkes *et al.*, 2017). As an example, the extent of *Z. marina* in Tralee Bay is shown (Fig. 5a).

Seagrasses belong to four major families: *Posidoniaceae*, *Zosteraceae*, *Hydrocharitaceae* and *Cymodoceaceae*. *Posidonia oceanica* is the main representative in the Mediterranean Sea (Fig. 5b). Recent estimates indicate that around 13 to 50 % of seagrass extent of *P. oceanica* was lost in the Mediterranean Sea between 1842 and 2009, with the remaining meadows becoming thinner and more fragmented for the last 20 years, leading to a substantial reduction of the capacity of carbon sequestration of this coastal ecosystem. The causes of *P. oceaninca* loss were both local and global disturbances, including climate change and the spread of invasive exotic species (Marbà *et al.*, 2014).

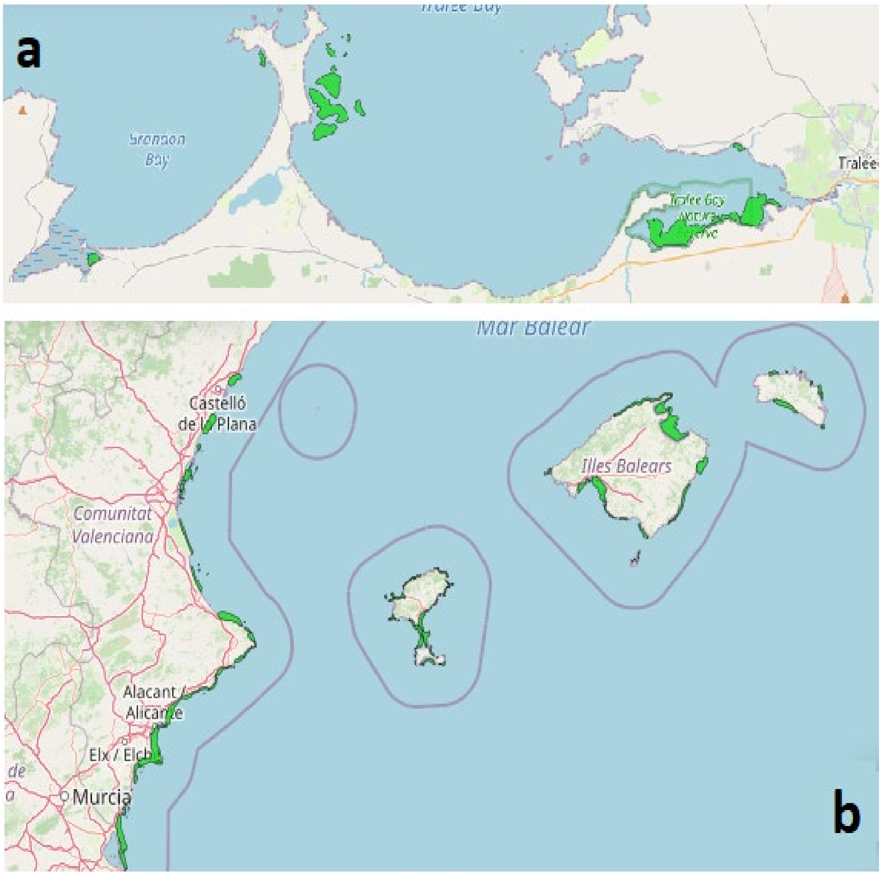

Figure 5. Distribution of seagrasses. (a) Zostera marina *in Tralee Bay (b)* Posidonia *oceanica around the Balearic Sea.*

2. **Macroalgal canopy cover.** This EOV shows the extent and distribution of macroalgal cover. The dominant species that integrate macroalgal forests are kelp and fucoid brown algae. Macroalgal are important primary producers in coastal ecosystems. The Environmental Protection Agency collect data on macroalgal biodiversity along the coast of Ireland. The locations and species identified over several years (2012-2020) are shown in Figure 6.

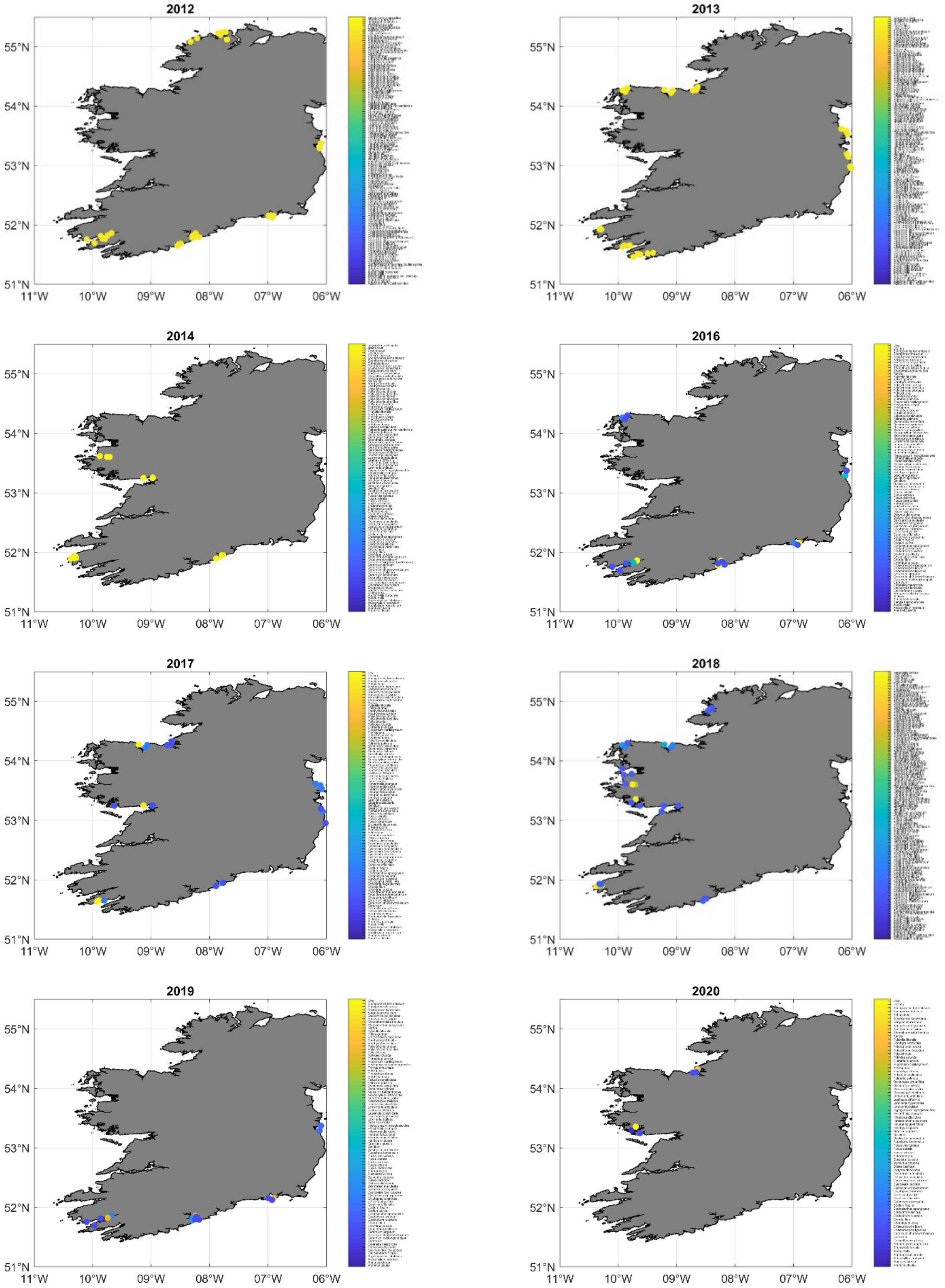

Figure 6. Macroalgae species and sites sampled in Ireland (2012-2020). Data from EPA

Figure 7 shows the total number of different macroalgae species identified each year, in an attempt to assess any change in biodiversity. The last year is characterised by the lowest diversity. However, it is important to notice that, because of different sampling efforts across the time period considered, and the fact that the

EPA sampling is focused on a reduced species list, this dataset is not comprehensive enough to evaluate the possible changes in macroalgal biodiversity in Ireland during this period.

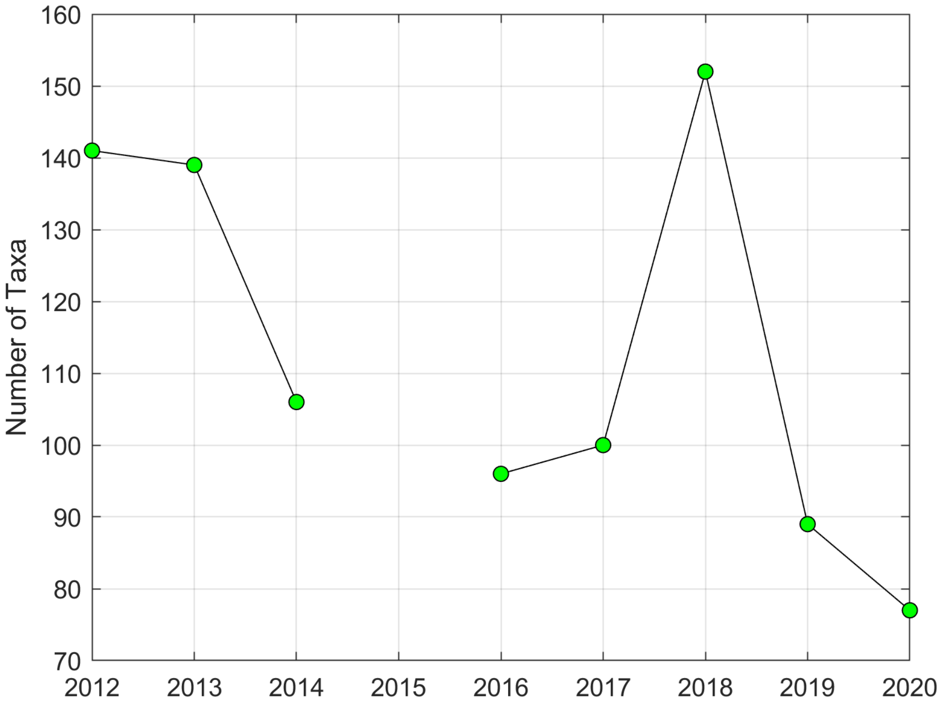

Figure 7. Number of different macroalgae taxa sampled each year

3. Live hard coral cover. This EOV provides an estimation of the current extent and distribution of any organisms forming hard coral reefs (Fig. 8). One of the main hard coral species of interest in the North Atlantic is *Lophelia pertusa*, which is registered on the OSPAR list of threatened or declining species. *Lophelia pertusa* is a habitat-forming species (keystone species), since it forms reefs that are home to a highly diverse biological community. However, it is also an extremely slow growing species that can be harmed by demersal fishing activities and oil extraction (Rogers, 2013).

Lophelia pertusa is a deep-water coral, living at depths ranging from 80 to 3,000 m, although most commonly found at depths between 200 to 1,000 m where there is of course no sunlight. As a result, the zooxanthellae, which typically grow in a symbiotic relationship with corals from other latitudes, are not present in *L. pertusa*. New polyps live and grow upon the $CaCO_3$ skeletons of previous generations. This calcifying organism is sensitive to changes in ocean acidification (lower pH and a shoaling of the aragonite saturation horizon make deep water habitats unsuitable for cold water corals).

The *L. pertusa* reefs were recognised as a threatened habitat in need for protection by the OSPAR Commission (Rogers, 2013). The main threat is the deep-sea trawling of fishing gear, which highly damages the coral. Considering the slow growth rate of these reefs, this type of fishing practice is unsustainable.

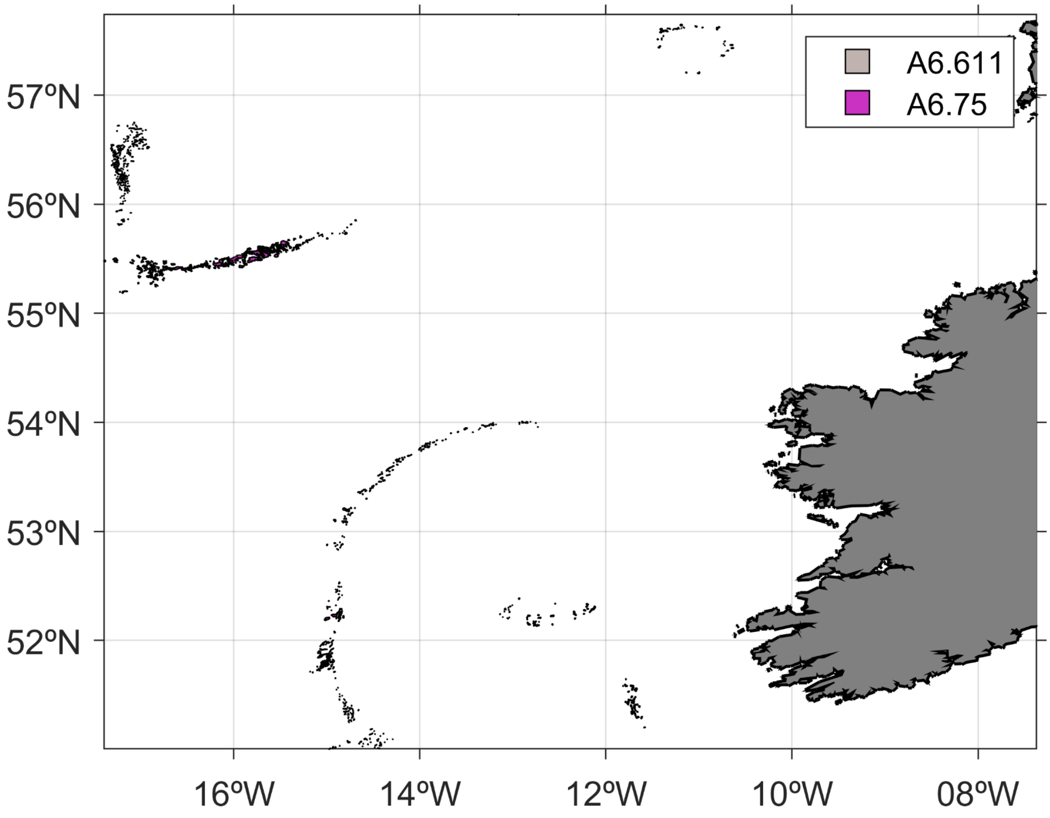

Figure 8. Distribution of EOV Live Hard Coral Cover in Irish waters. The meaning of the EUNIS codes here are A6.611: Deep-Sea Lophelia pertusa *reefs; A6.75 Carbonate mounds.*

2.2. Aquaculture sites

Data on aquaculture sites is publicly available for download and visualisation on the Ireland's Marine Atlas[13] webpage. The available data covers all currently licensed extensive and intensive aquaculture sites in Ireland and includes spatial information such as site shape and area, geographical location, licence status and culture species.

Extensive aquaculture is defined in Regulation 3(iii) of the Aquaculture (Licence Applications) (Amendment) Regulations 2018 as "*aquaculture activities where there is no external supply of feed and the culture depends entirely on natural processes for production and supply of feed*". Shellfish (echinoderms, molluscs and crustacea) and seaweed aquaculture fall within this definition. The method of aquaculture employed within an aquaculture site is contingent on and number of factors, including, *inter alia*, the site's location on the foreshore (littoral or sublittoral), seabed topography (reef or sediment) and the culture species. In general, the primary species cultured as part of extensive aquaculture in Ireland are the Blue Mussel (*Mytilus edulus*) and the pacific oyster (*Crassosstrea gigas*). The Blue Mussel is generally cultured in sublittoral areas, either via suspended longline structures or via 'bottom culture' - seeding of spat directly to the seabed within an

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[13] http://atlas.marine.ie/#?c=53.4652:-10.4150:7

aquaculture site and subsequent harvesting via dredging. The Pacific Oyster is usually cultured in intertidal sandflats and mudflats via the bag and trestle method.

Intensive aquaculture is defined in Regulation 3(iii) of the Aquaculture (Licence Applications) (Amendment) Regulations 2018 as *activities where the biomass produced is beyond that which could be naturally supported without the provision of additional feed*. This definition captures finfish pen aquaculture methods. Finfish aquaculture in Ireland largely focuses on Salmon. Marine finfish pen aquaculture is carried out in sublittoral areas and can involve the use of 20+ pens depending on the licenced Maximum Allowable Biomass for that site. Finfish sites in Ireland tend to occur in areas lying between 20 – 50 m depth and can lie over reef or sediment habitats.

2.3. Sea lice monitoring

Sea lice are copepod crustaceans that are parasitic to different marine fish and are known to cause a huge economic loss to the salmon farming industry. In 1991, a Sea Lice Monitoring Programme for Finfish Farms in Ireland (Jackson and Michin, 1993) was initiated by the Department of the Marine, and the monitoring was extended nationwide in 1993. It was not until May 2000 that the standard procedures for sea lice monitoring were formally published (*Monitoring Protocol No. 3 for Offshore Finfish Farms — Sea Lice Monitoring and Control*).

The continuous monitoring of the abundance of sea lice in salmon farms revealed the struggles faced by the industry to achieve the low levels of infestation demanded by the national monitoring programme. In order to tackle such difficulties, the Department of Agriculture, Fisheries and Food, together with the Marine Institute and Bord Iascaigh Mhara, developed a working strategy outlining a comprehensive range of measurements to provide for an increased control of sea lice (O'Donohoe *et al.*, 2021). The guidelines were published in "*A strategy for the improved pest control on Irish salmon farms*" (2008).

Sea lice management in salmon farms involves applying different techniques to control the abundance of the parasite and to mitigate the impact on the livestock. Among the different existing approaches to delouse the salmon are: (a) administration of veterinary medicines, either topically or in-feed; (b) cleaner fishes, such as the lumpfish *Cyclopterus lumpus* (Imsland *et al.,* 2014) provide positive effects as part of a sea lice management plan; (c) filtration methods have also proven to be an efficient method for removing all stages of sea lice (O'Donohoe and McDermott, 2014); (d) thermal and hyposaline treatments control sea lice numbers on salmon farms in the West of Ireland, especially during the summer months (McDermott *et al.,* 2021).

As part of the national monitoring programme, farmed stocks in Ireland are inspected on 14 occasions throughout the year. Each examined fish is inspected individually for all mobile sea lice, which are then removed and preserved in 70 % ethanol. The mean number of sea lice per fish is calculated.

3. Case studies

3.1. Sea lice in Deenish Island salmon farm, MHWs and oxygen concentration

The Atlantic salmon (*Salmo salar*) is a ray-finned fish spread across the North Atlantic Ocean and in the rivers flowing into this ocean. Hatching takes place in river streams and the individuals spend the first stages of their lives in the rivers. The young salmon usually stays in the river for about two to three years, passing through different stages of development: *alevin*, *fry*, *parr* and *smolt*. Smolts then migrate downstream towards the ocean, usually between March and June, while undergoing different physiological adaptations to prepare for salty conditions. The salmon originating from the rivers in Ireland migrate to their feeding grounds in the Norwegian Sea and the coasts of Greenland. After some years in the sea, the adults return to the same freshwater stream where they originated for spawning.

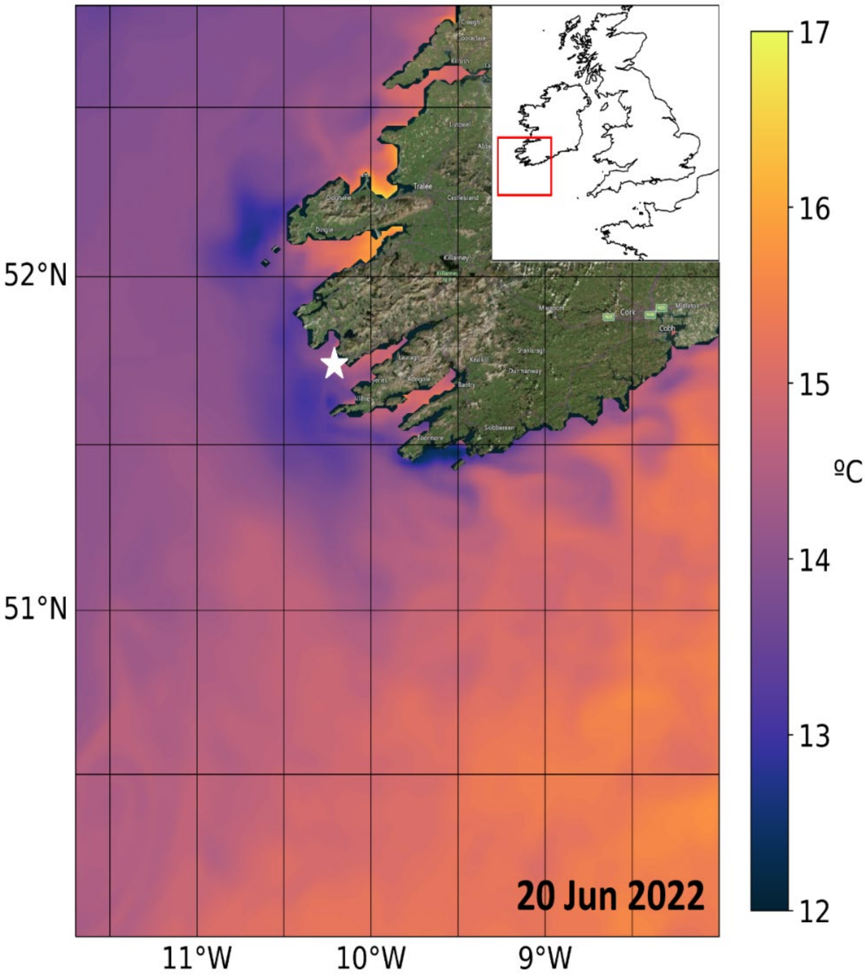

Figure 9. Location of the Deenish Island salmon farm off SW Ireland. The map shows the sea surface temperature distribution on 20 June 2022 from the UK MetOffice Northwest Shelf model, which will be used for a MHW forecasting system in the region.

Nearly all consumption of salmon comes from aquaculture. In fact, salmon is the 9th species farmed in aquaculture by volume, with a total worldwide fish production of around 2.5 million tons per annum (FAO, 2020). The largest producers in the Atlantic Ocean are Norway (52.63 % share of global production), the UK (6.81 %), Canada (5.06 %), the Faroe Islands (3.24 %), the USA (0.66 %), Iceland (0.55 %) and Ireland (0.49 %). Most salmon are produced in square or circular cages at the sea, 10 to 32 m across and 10 m deep, keeping up to 90,000 fish. The cause of mortality at salmon farms is unknown or not disclosed in 65 % of the cases. Sea lice is estimated to explain about 15 % of the mortality, with other diseases (11 %) and algal blooms (9 %) representing the remaining causes of mortality.

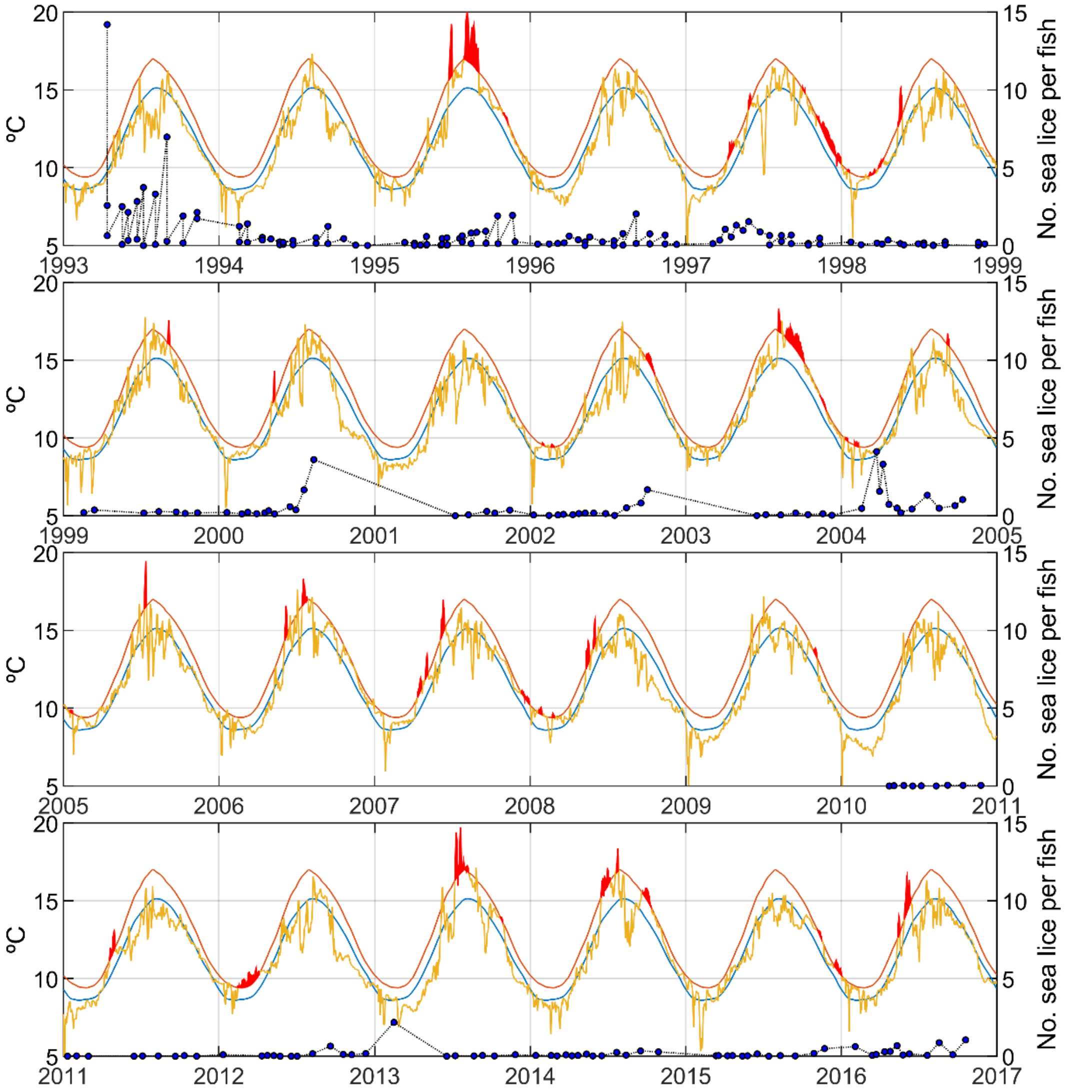

Figure 10. Surface MHW's at the Deenish Island salmon farm according to the Southwest of Ireland model for 1993-2016. The baseline climatology (blue), 90-th percentile threshold (orange) and the actual seawater temperature series (yellow) are shown (left Y-axis). MHW events are highlighted in red. The total number of the sea lice Lepeophtheirus salmonis *per fish are represented by the blue filled in circles (right Y-axis).*

As described in Section 2.3 above, sea lice are frequently occurring ectoparasites, small copepod crustaceans that attach to different marine fish, including salmonids. The salmon lice, *Lepeophtheirus salmonis* and *Caligus elongatus* are the two most important species found in Irish waters. Sea lice infestation causes severe animal welfare problems, ecological impacts and a massive economic loss to the global salmon farming industry, estimated at USD 400 - 600 million per year.

One important stakeholder in the Irish waters is MOWI, a world's leading seafood company, primarily focused on fish farming, especially salmon. The Deenish Island salmon farm is owned by MOWI and is located at 51.739N 10.213W outside of Kenmare Bay (Fig. 9). In this case study, two different *Extreme Marine Events* were considered jointly: Marine Heat Waves and low dissolved oxygen concentration events. The occurrence of these *Extreme Marine Events* at the Deenish Island salmon farm was investigated and linked to the total abundance of the sea lice *Lepeophtheirus salmonis* per fish.

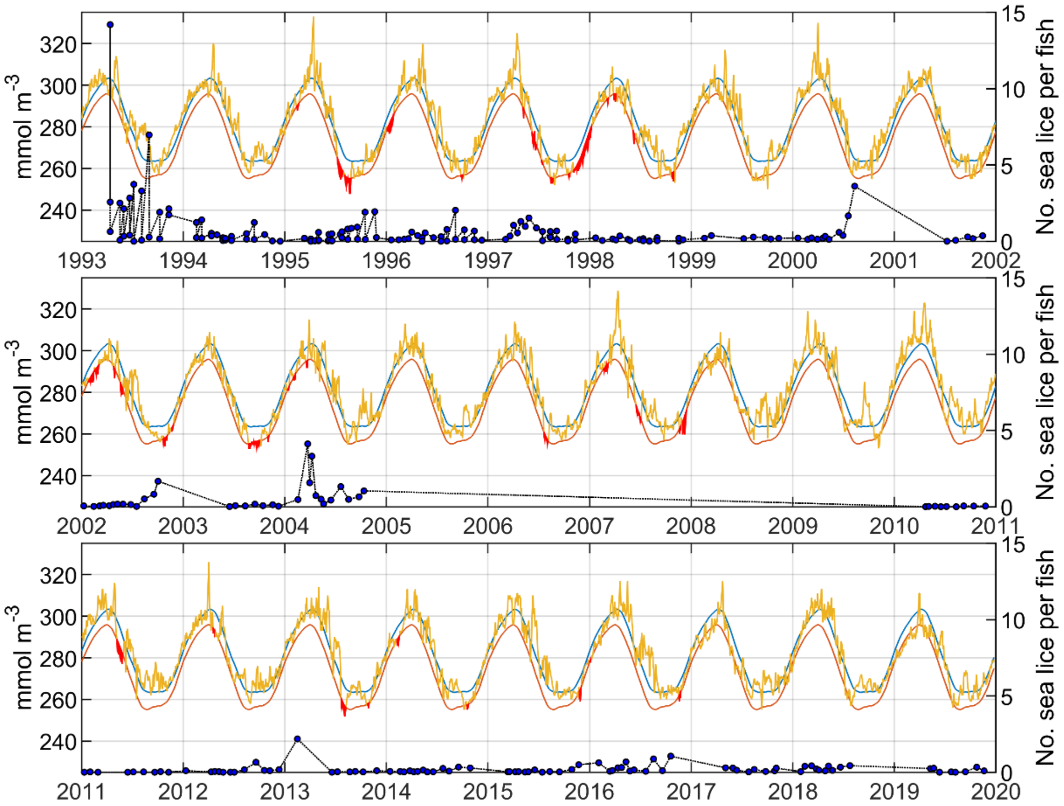

Figure 11. Surface dissolved oxygen concentration at the Deenish Island salmon farm according to the CMEMS' Atlantic Iberian-Biscay-Irish Biogeochemistry Multi-Year Non-Assimilative Hindcast Product for 1993-2019. The baseline climatology (blue), 10-th percentile threshold (orange) and the actual oxygen concentration series (yellow) are shown (left Y-axis). Low DO events are highlighted in red. The total number of the sea lice Lepeophtheirus salmonis *per fish are represented by the blue filled in circles (right Y-axis).*

The 1993-2016 sea surface temperature series at the Deenish Island salmon farm was obtained from the Southwest of Ireland hydrodynamic model (Nagy *et al.*, 2021) described in Section 1.1. Then, using a reference climatology period from 1993 to 2014, the number, duration and intensity of Marine Heat Waves at the farm were determined following the methodology described in Hobday *et al.* (2016).

When looking at the 1993-2016 time series (Fig. 10), one aspect that deserves particular attention is the high internannual variability concerning the number, duration and intensity of Marine Heat Waves. There are years when MHWs are absent and, in contrast, there are years characterized by intense or long-lasting MHWs. Another aspect of interest is the difference between intense and long-lasting MHWs, and the different impact that these events have on the marine biota. An example of an intense but short-lived Marine Heat Wave is the one reproduced by the model in late spring - early summer 2005. On the other hand, there are long lasting but weak MHWs, such as the one occurring during the fall of 1997. Even though the word "weak" is used here, the seawater temperature was sustained above the 90th percentile threshold for several months. When questioned about which of these MHW characteristics –either duration or intensity– would be the most relevant in relation to the level of stress experienced by marine organisms like farming salmon, stakeholders replied that the long-lasting events would probably be the most harmful. Remarkably, there also exist Marine Heat Waves that are both intense and long lasting, such as the one reported by the model in summer 1995 at the Deenish Island salmon farm. Such events are likely to be the most devastating. Finally, no obvious trends were identified in the frequency, duration or intensity of MHWs at this aquaculture site.

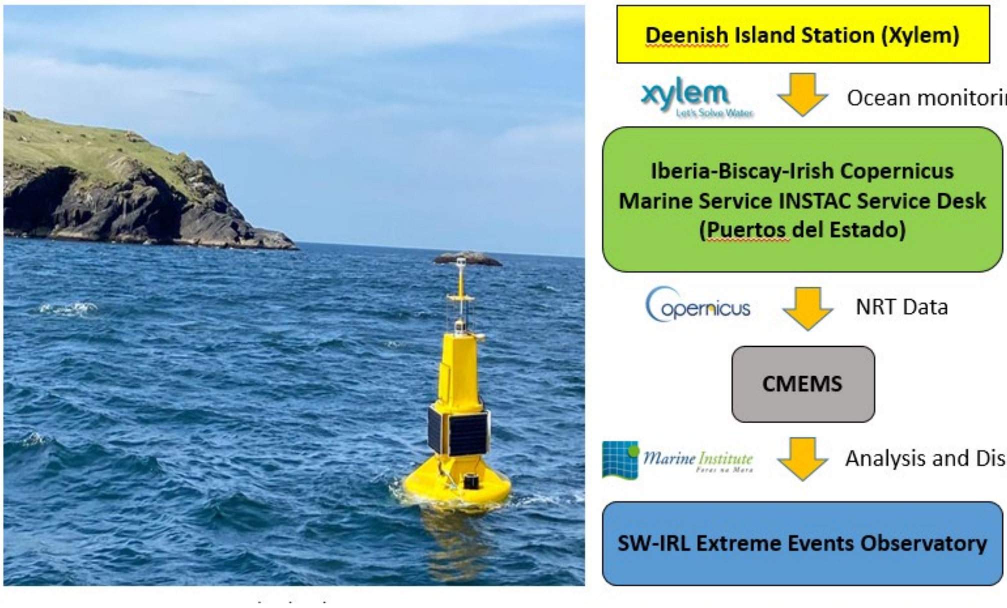

Figure 12. The Deenish Island EuroSea monitoring station developed by Xylem in cooperation with MOWI, MI and CSIC and deployed in April 2022 (left). The measurements from this station will be available through CMEMS via the Iberia-Biscay-Irish Copernicus Marine Service in-situ *Thematic Centre (INS TAC) Service Desk (operated by Puertos del Estado). A web portal is currently under development by the EuroSea WP6 partners that will make this data accessible to the stakeholders, together with predictions of* Extreme Marine Events *in SW Irish waters.*

The 1993-2019 surface DO (mmol m^{-3}) at the farm was derived from the CMEMS' Atlantic Iberian-Biscay-Irish Biogeochemistry Multi-Year Non-Assimilative Hindcast Product. The procedure described in Section 1.2 was followed to identify events with anomalously low levels of dissolved oxygen concentration (Fig. 11). It is possible to recognise some correspondence between the MHW events in Figure 10 and the low DO events in Figure 11. For example, the intense MHW in summer 1995 and the low DO event the same year. In any case, the lower threshold for salmon farming of 5 mg L^{-1}, or 156.25 mmol m^{-3} is never exceeded.

The total number of *Lepeophtheirus salmonis* per fish recorded at the Deenish Island salmon farm are reported here together with the temperature and DO series. According to Dalvin *et al.* (2020), temperature is a strong influencer of biological processes in salmon lice, with development rate increased at higher temperatures. However, there are many other factors apart from seawater temperature influencing the populations of sea lice. Since these other factors need to be taken into consideration, it is difficult to appreciate any connection between the sea lice abundance and the temperature and DO series shown here. In addition, sea lice numbers are affected by delousing treatments: whenever the number of sea lice in the farm exceeds a threshold that threatens the fish health, mitigation measurements are applied.

In this study, hydrodynamic and biogeochemical model data was used because of the lack of *in-situ* measurements and the need of having multidecadal time series to investigate long-term trends associated to climate change. However, models cannot reproduce local effects caused by the farming activity. In addition, models do not account for local, episodic, high-biomass phytoplankton blooms that trigger deoxygenation events when the bloom subsides (e.g. *Karenia mikimotai* bloom; Silke *et al.*, 2005). For example, the biogeochemical model used here would not capture sub-optimal oxygen concentrations due to the excessive decomposition of organic matter at the farm. This highlights the importance of deploying monitoring platforms to produce *in-situ* observations. In this regard, the recent deployment by Xylem of a monitoring station at the Deenish Island salmon farm will be of great benefit to assess environmental impacts on the farming activity. As part of the activities in EuroSea, a web portal providing real-time observations from the monitoring buoy at Deenish Island is being developed. This portal will provide stakeholders with forecasts of extreme marine events too (Fig. 12).

3.2. Tracking Heat Waves impacting reproductive ecology of tuna in the Mediterranean Sea

The fate of marine fish species depends mostly on the survival of their early life stages (tinny eggs; larvae) that live for a few days in the first meters of the water column. Environmental conditions where the fish reproduce will in part determine the recruitment success of the early life stages (Ciannelly et al. 2015). Some species, such as the emblematic bluefin tuna (*Thunnus thynnus*), perform long migrations every year from the Atlantic Ocean foraging areas to specific areas in the Mediterranean Sea where they reproduce. Other tuna species, such as albacore (*Thunnus alalunga)* and bullet tuna (Auxis rochei) spend most of their life in the Mediterranean Sea migrating to specific areas where they aggregate during the reproductive season (Alemany *et al.*, 2010, Reglero *et al.*, 2019, Muhling *et al.*, 2017).

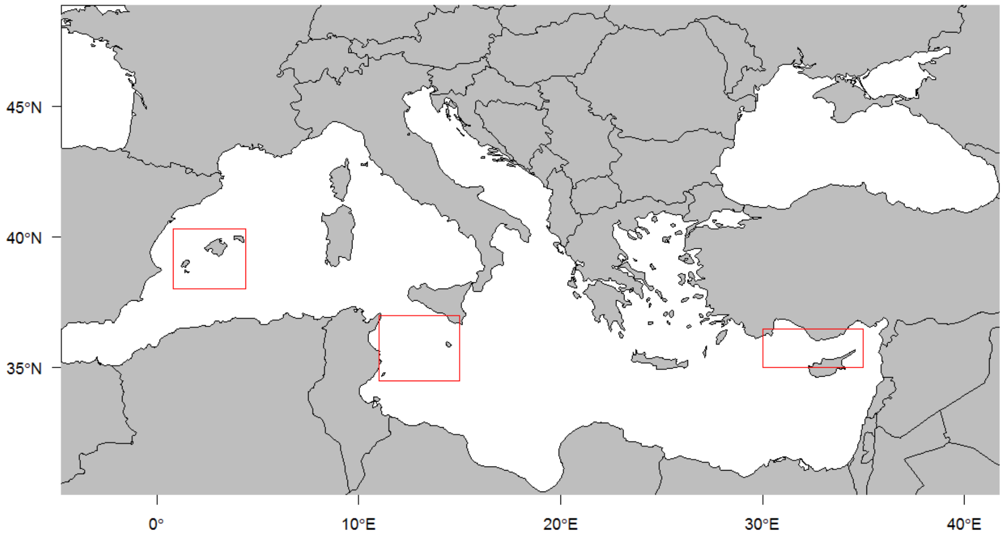

Figure 13. The Mediterranean Sea, red boxes indicate the geographical limits of the tuna spawning grounds (Balearic Sea in the Western, Tunisia-Malta in the Central, and Cyprus in the Eastern Mediterranean) used for the spatial integration of the temperature values. Figure from Alvares-Berastegui (2020).

The oceanographic conditions in these spawning grounds affect a number of ecological processes that determine the growth and survival during the early life stages, directly affecting the population recruitment, defined as the addition of new individuals to the population in the following generations. Understanding these processes is paramount to advance the fisheries assessment and management approach that integrates the effect of oceanographic variability in the populations of the harvested fish species. An international panel of scientists coordinated by the International Commission for the Conservation of Atlantic Tunas (ICCAT) use information about the tuna populations during these developmental stages to estimate larval abundances and survival rates, which informs about the number of adults in the spawning areas (Ingram *et al.* 2017) and the potential recruitment for a specific year (Reglero *et al.* 2019). The calculation of these parameters relies on the hydrographic conditions in the spawning grounds during the reproductive season. This is one successful example of how to integrate ecological processes in relation to oceanography in the assessment process applied to evaluate the state of the populations for establishing sustainable levels of fishing activity.

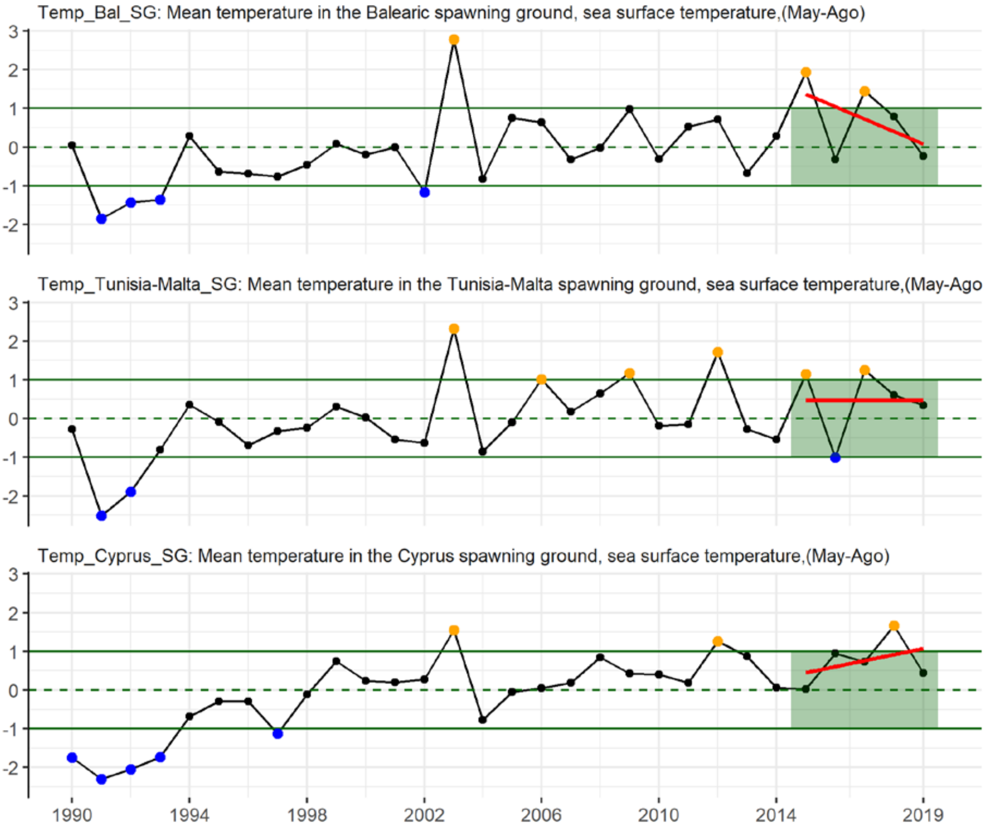

*Figure 14. Mean sea surface temperature (May - August) in the Western Mediterranean Spawning ground (Balearic Sea); Central Mediterranean (Tunisia; South Sicily) and Eastern Mediterranean (Cyprus). Data from the Copernicus MEDSEA hydrodynamic model. Indicators of ecosystem status. Time series of temperature values are presented after standardization to the mean. Values ≥1 std are orange. Values ≤*1 std are blue. Red trend lines are for the last 5 years and were fit with a linear model.

One of the most relevant hydrographic variables influencing the geographical location and timing of reproduction and the survival of the eggs and larvae is the water temperature in the mixed layer depth, where tuna eggs and larvae are distributed (Reglero *et al.*, 2019, Harford *et al.,* 2017). Indicators providing information on the temperature variability in that depth range before, during and after the spawning season of tuna provide a valuable source of information for the decision making process during the meetings conducted by the fisheries assessment working groups (WGs). The WGs, in many cases, have to evaluate whether abundance indices of tunas for a particular year are representative of the population status, or the result of particular environmental conditions. Getting access to quantitative information on hydrodynamic process affecting recruitment is the most common approach to identify potential interactions of environmental effects and population dynamics during these working groups (Marshall *et al.*, 2019).

In this study, we give information on the variability of seawater temperature during the reproductive season of various tuna species in the main spawning grounds in the Mediterranean.

The three major spawning areas in the Mediterranean Sea for tuna species are located: 1) in the Western Mediterranean around the Balearic Islands, 2) in the Central-Southern Mediterranean near Tunisia, Malta and Sicily Waters, and 3) in the Eastern Mediterranean in the Levantine Sea, near Cyprus and Turkey (Fig. 13). We estimated one temperature indicator for these three areas using data extracted from the daily resolution product of the Copernicus hydrodynamic model "CMEMS MED-MFC", the Mediterranean Sea Physics Reanalysis and Forecast (Simoncelli *et al.*, 2014), at the 10.5 meter depth, as a proxy for the mean temperature in the mixed layer depth.

This indicator is estimated as the daily temperature data for each spatial region averaged from May to August. The values of these indicators were scaled to the standard deviation (Fig. 14). These types of indicators are intended to provide a general view of the interannual hydrographic scenarios for the whole tuna species community. They are estimated at a temporal range that covers broadly the reproductive season of the different tuna species such as bluefin tuna, albacore tuna or bullet tuna in the three areas. In general, tuna species begin to reproduce earlier in the Eastern than the Central and Western Mediterranean. Besides, the reproductive season can vary slightly among species, bluefin tuna have the shortest and albacore and bullet tuna have the longest spawning period. Therefore, these indicators (Fig. 14) give information on the general thermal conditions in the three areas over time during the potential reproductive window for all tuna species.

Most of the fisheries assessment models worldwide and in particular in the Mediterranean Sea are conducted without considering the influence of the oceanographic processes over the harvested fish populations (Skern-Mauritzen *et al.*, 2016). The relevance of the indicators here presented and its application to improve the fisheries assessment of bluefin tuna is a good example of how to advance the integration of the oceanographic state on the sustainability of marine ecosystems. These indicators are the first ones accepted by the ICCAT sub-group on Ecosystems, as part of the environmental component of the "Ecosystem Report" Card (Alvarez-Berastegui, 2020), the main tool of the commission for the development of an Ecosystem Based Approach to Fisheries. Merging research in the ecology of harvested species and the effects of oceanography is an opportunity to advance towards a new paradigm of fisheries assessment and management now possible due to recent advances on operational oceanography data quantity and quality.

3.3. Ocean Acidification: *Lophelia pertusa* reefs and long-term decrease in pH

The 1993-2020 near-seafloor pH data from the CMEMS' Atlantic Iberian-Biscay-Irish Biogeochemistry Multi-Year Non-Assimilative Hindcast Product was used to determine the long-term linear trend in pH around the Porcupine Bank where *Lophelia pertusa* reefs are present (EMODnet Seabed Habitats Live Hard Coral Cover EOV). The 2-D distribution of the pH linear trend was overlaid with the habitat information of this EOV. The distribution of *Lophelia pertusa* reefs are shown in Figure 15.

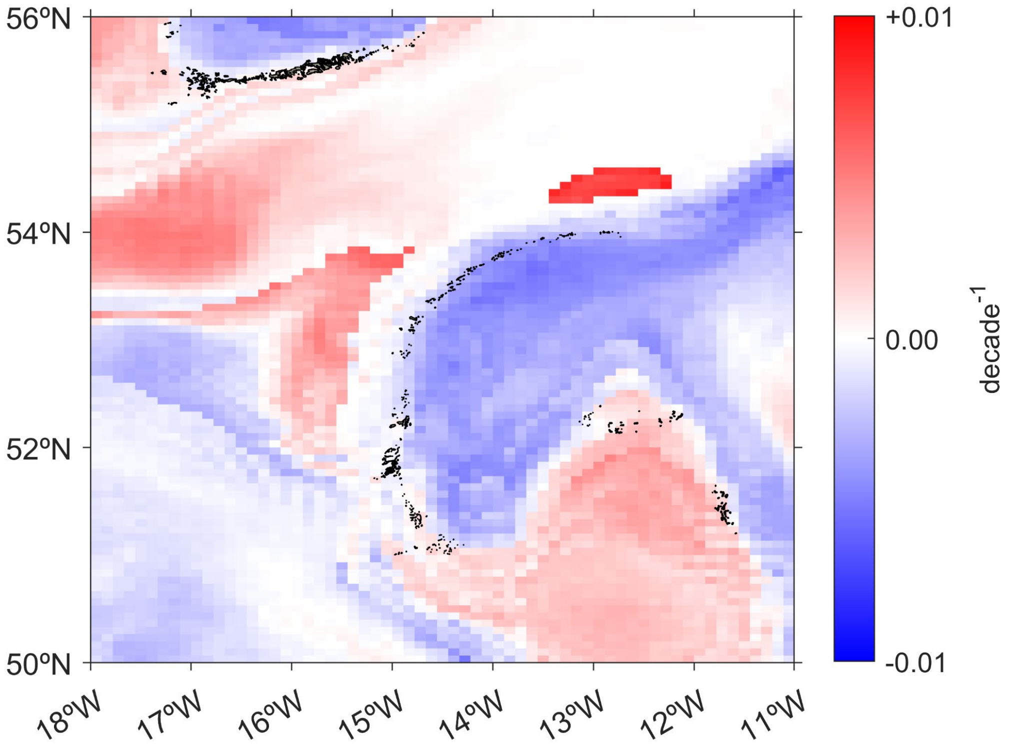

Figure 15. Model distribution of the multiyear linear trend of seafloor pH around the Porcupine Bank overlaid with the distribution of Lophelia pertusa *reefs.*

The near-seafloor pH trend appears highly correlated with bathymetry. Negative trends (acidification) are evident in shallower areas, whereas the model predicts a positive trend in deeper areas. However, it is highly likely this is an artefact in the model, since biogeochemical model less well developed when compared to physical models.

The reefs are predominantly located in areas of transition between positive and negative pH trends. Therefore, it is difficult to extract conclusions about the future *Lophelia pertusa* reefs in a context of climate change and ocean acidification. When *L. pertusa* is exposed in the laboratory to different environmental conditions of temperature, $p\mathrm{CO}_2$, and food availability, it is known that elevated $p\mathrm{CO}_2$ values lead to decreased net calcification rates (Büscher *et al.*, 2017). The same authors conclude that, under a future climate change scenario, dissolution and decreased net growth in acidic conditions would endanger the future of cold-water coral ecosystems due to bioerosion and dissolution of the reefs.

3.4. Acidification: oyster farming in Tralee Bay and long-term decrease in pH

The largest aquaculture site in Ireland, as described by the dataset in Section 2.2, is the Tralee Bay oyster fishery (Fig. 16). It is one of the few self-seeding Native Wild Irish Oyster Fisheries in Europe. The Tralee Bay Oyster fishery is one of the largest self-reproducing oyster beds in Europe. As such, and to provide an example case study of the potential impacts of acidification on aquaculture, the long-term pH linear trend averaged over this area was determined (Fig. 17).

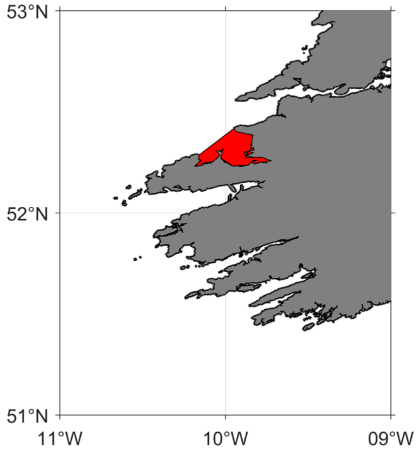

Figure 16. The Tralee Bay oyster farming site

The 1993-2020 pH time series was derived from the surface layer of the CMEMS' Atlantic Iberian-Biscay-Irish Biogeochemistry Multi-Year Non-Assimilative Hindcast Product. A linear trend of -0.016 decade^{-1} is reported by the model (Fig. 17), reflecting the generalized effect of ocean acidification.

Assuming a constant linear trend during the rest of the 21th century, we estimated that the average pH at the Tralee Bay oyster fishery in 2100 will be approximately 7.94. A decreased pH of the ocean will have negative effects for calcifying organisms such as bivalves, with larval stages being more sensitive to increasing acidic conditions. Previous research on the influence of seawater acidification on *Ostrea edulis* larvae development showed that acidified seawater had a markedly negative effect on the larval shell length. When *O. edulis* larvae were grown under changing pH conditions, the slowest growth and smallest length were observed in the larvae cultivated at the lowest pH (Oettmeier, 2007). Further research will be needed to understand the impact that ocean acidification will have on shellfish aquaculture around the world.

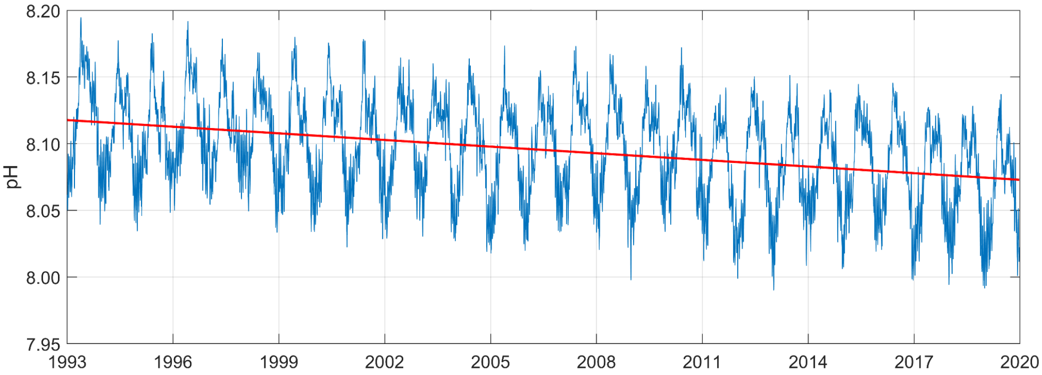

Figure 17. IBI pH trend spatially-averaged over the Tralee oyster farming area

Conclusion

In this report, the link between selected *Extreme Marine Events* (marine hetwaves, deoxygenation and acidification) with the marine biota was examined using selected case studies. The following conclusions can be drawn from this report:

1. There is a need to increase the amount of *in-situ* ocean observations of the marine environment to properly evaluate the impact of climate change on the biological communities.Remote-sensing and modelling provide the general picture on large scales, but sometimes fail to reproduce the small-scale features that affect a particular habitat or aquaculture farming site. In this sense, extending the observational network, with efforts such as the recent deployment of a EuroSea monitoring station at the Deenish Island salmon farm, represents important progress.

2. The interaction between multiple co-stressors and their effects on keystone species needs to be considered as part of further case studies. Ocean warming, deoxygenation and acidification are interrelated and this exacerbates the impacts on marine communities, and needs to be taken into consideration when anomalous events occur.

3. Finally, a higher effort of biological sampling and data available in an easy-to-share format would greatly improve temporal information collected on biologically sensitive organisms. To improve risk assessments and our understanding of the impacts of extreme marine events on biologically important ecosystems, improved coordination across the scientific disciplines (biological, chemical and physical) is needed. The formation of rapid response teams to take measurements when extreme marine events occur would greatly improve our understanding and adaptation plans.

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